

## Specification

### Title of the Invention

[0001]      Optical Low Pass Filter

### Background of the Invention

[0002]      The present invention relates to an optical low pass filter (OLPF) provided in an imaging apparatus such as a digital camera.

[0003]      Recently, digital cameras have been widespread. For digital cameras employing solid-state imaging elements, such as a CCD (Charge Coupled Device), used as an imaging surface, it is important to avoid a moiré effect or an occurrence of false colors.

[0004]      For this purpose, an optical low pass filter (OLPF) is generally provided between a photographing lens (i.e., an imaging optical system) and the imaging surface so that the high spatial frequency components are removed from an image formed on the imaging surface.

[0005]      Generally, the imaging element, or the CCD is formed to have a rectangular shape, and a plurality of pixels are arranged at regular interval, in a matrix, along longer and shorter sides of the rectangular shape. In this specification,

the term "horizontal direction" refers to a direction corresponding to the longer side of the rectangular imaging element (e.g., CCD), and the "vertical direction" refers to a direction corresponding to the shorter side of the imaging element.

[0006] A conventional OLPF is configured to have three cemented birefringence plates (which will be referred to as a three-element OLPF), or two birefringence plates with a predetermined wavelength plate sandwiched therebetween.

[0007] A Japanese Patent Provisional Publication No. 2000-56268 (hereafter, referred to as a document 1) discloses a conventional three-element OLPF. The three-element OLPF disclosed in the document 1 has three birefringence plates having separation directions of  $0^\circ$ ,  $+45^\circ$  and  $-45^\circ$ , respectively with respect to the horizontal direction. In general, the separation direction in which a divided ray is directed is represented by an angle with respect to the horizontal direction.

[0008] Fig. 9 is an MTF (Modulation Transfer Function) map illustrating an effect of the conventional three-element OLPF. In Fig. 9, a horizontal axis and a vertical axis indicate normalized values of spatial frequencies. Specifically, the horizontal axis in the MTF map of Fig. 9 represents the spatial frequencies in the horizontal direction (X direction), and the vertical axis in the MTF map of Fig. 9 represents the spatial

frequency in the vertical direction (Y direction). In Fig. 9, a region A transmits light with a highest transmittance (MTF value: 0.8-1), a region B has a second highest transmittance (MTF value: 0.6-0.8), a region C has a third highest transmittance (MTF value: 0.4-0.6), and a region D has a fourth highest transmittance (MTF value 0.2-0.4). A region E hardly transmits light (MTF value: 0.0-0.2). Note that the definition of the regions A-E applies in all the MTF maps in this specification.

[0009] In the conventional OLPF having a characteristic shown in Fig. 9, each of the regions A-D is formed substantially symmetrically both in the vertical direction and horizontal directions. With this configuration, the high spatial frequency components can be eliminated both in the vertical direction and in the horizontal direction in a similar manner. The way the transmitting regions (i.e., the regions A-D) expand will be referred to as a cut-off directionality. The conventional OLPF having the characteristic shown in Fig. 9 has an excellent cut-off directionality such that the characteristic thereof has little direction dependency.

[0010] As shown in Fig. 9, the region E in the three-element OLPF disclosed in the document 1 is relatively small. That is, the normalized frequency component of -0.4 or less, or +0.4 or more is not sufficiently suppressed. The function of suppressing/eliminating the high spatial frequency components

provided by the OLPF will be referred to as a cut-off function.

[0011] As described above, the three-element OLPF disclosed in the document 1 does not have a sufficient cut-off function, although the three-element OLPF has an excellent cut-off directionality. Therefore, the three-element OLPF passes undesired frequency components, which may deteriorate the quality of the image.

[0012] A Japanese Patent No. 2840619 (hereafter, referred to as a document 2) discloses a conventional three-element OLPF in which three birefringence plates having separation angles of  $-45^\circ$ ,  $0^\circ$  and  $+45^\circ$ , respectively are provided.

[0013] Fig. 10 shows the MTF map of the three-element OLPF disclosed in the document 2. By making a comparison between Fig. 10 and Fig. 9, it is understood that the region E of the OLPF shown in Fig. 10 is relatively large, i.e., the OLPF shown in Fig. 10 has an excellent cut-off function.

[0014] However, the regions A-D expand greater in one direction (the direction PL in Fig. 10) than another direction (the direction PS) which is perpendicular to the direction PL. When this OLPF is used, the degree of blur in the PL direction is smaller than the degree of blur in the PS direction. That is, the cut-off directionality of the OLPF in document 2 is inferior to the cut-off directionality of the OLPF in document 1.

[0015] In the following description, when the MTF maps are

referred to, the direction in which each region (A, B, C and D) expands greatest is indicated as the direction PL, and the direction in which each region expands smallest is indicated as the PS direction.

[0016] As described above, the three-element OLPF disclosed in the document 2 does not have a sufficient cut-off directionality, although it has an excellent cut-off function. Therefore, when the three-element OLPF of document 2 is employed, although the excellent cut-off function is expected, due to the lopsided cut-off directionality, the quality of a captured image is lowered since the resolution of the captured image differs depending on the direction.

#### Summary of the Invention

[0017] The present invention is advantageous in that it provides a three-element optical low pass filter which has both an excellent cut-off function and an excellent cut-off directionality.

[0018] According to an aspect of the invention, there is provided an optical low pass filter, which is provided with a first birefringence plate that divides an incident ray into two rays, a second birefringence plate that divides an incident ray into two rays, and a third birefringence plate that divides an incident ray into two rays. In this structure, the first

birefringence plate, the second birefringence plate and the third birefringence plate are cemented to each other, light passed through the first birefringence plate passing through the second birefringence plate and then passing through the third birefringence plate. Further, a separation angle  $\theta_s$ , representing a difference between separation directions in which adjacent ones of the first, second and third birefringence plates divide their respective incident rays, satisfies a condition:

$$46^\circ \leq \theta_s \leq 60^\circ.$$

[0019] With this configuration, both an excellent cut-off function and an excellent directionality are enhanced.

[0020] Optionally, the separation angle  $\theta_s$  may satisfy a condition:

$$46^\circ \leq \theta_s \leq 52^\circ.$$

[0021] Still optionally, when a separation amount, representing a distance by which the two rays divided by one of the first, second and third birefringence plates are away with respect to each other, is denoted by  $\delta_1$  for the first birefringence plate, the separation amount for the second birefringence plate is denoted by  $\delta_2$ , and the separation amount for the third birefringence plate is denoted by  $\delta_3$ , the optical low pass filter may satisfy a condition:

$$\delta_1 = \delta_3 \neq \delta_2.$$

[0022] Still optionally, the separation amount for the

second birefringence plate  $\delta_2$  may satisfy a condition:

$$0.5 \cdot \delta_1 \leq \delta_2 < 1.0 \cdot \delta_1.$$

[0023] In a particular case, the separation angle  $\theta_s$  may be defined by a following equation:

$$\theta_s = |\theta_1 - \theta_2| = |\theta_2 - \theta_3|,$$

where  $\theta_1$  is an angle that the separation direction in which the first birefringence plate divides its incident ray forms with respect to a horizontal direction corresponding to a longer side of a rectangular shape of an imaging element to be used together with the optical low pass filter,  $\theta_2$  is an angle that the separation direction in which the second birefringence plate divides its incident ray forms with respect to the horizontal direction, and  $\theta_3$  is an angle that the separation direction in which the third birefringence plate divides its incident ray forms with respect to the horizontal direction.

#### Brief Description of the Accompanying Drawings

[0024] Fig. 1 schematically shows a configuration of an optical low pass filter (OLPF) according to an embodiment of the invention;

[0025] Fig. 2 shows a MTF map when a separation angle of the OLPF according to the embodiment is set to be  $46^\circ$ ;

[0026] Fig. 3 shows a MTF map when the separation angle of the OLPF according to the embodiment is set to be  $48^\circ$ ;

[0027] Fig. 4 shows a MTF map when the separation angle of the OLPF according to the embodiment is set to be  $52^{\circ}$ ;

[0028] Fig. 5 shows a MTF map when the separation angle of the OLPF according to the embodiment is set to be  $55^{\circ}$ ;

[0029] Fig. 6 shows a MTF map of the OLPF according to the embodiment when the separation angle is  $48^{\circ}$  and the a separation amount is 1.0;

[0030] Fig. 7 shows a MTF map of the OLPF according to the embodiment when the separation angle is  $48^{\circ}$  and the a separation amount is 0.8;

[0031] Fig. 8 shows a MTF map of the OLPF according to the embodiment when the separation angle is  $48^{\circ}$  and the a separation amount is 0.6;

[0032] Fig. 9 shows an MTF map illustrating of one of conventional three-element OLPFs; and

[0033] Fig. 10 shows an MTF map of one of the conventional three-element OLPFs.

#### Detailed Description of the Embodiments

[0034] Hereinafter, an embodiment according to the invention is described with reference to the accompanying drawings.

[0035] Fig. 1 schematically shows a configuration of an optical low pass filter (OLPF) 10 according to an embodiment



of the invention. As shown in Fig. 1, the OLPF 10 has three birefringence plates 1-3, each of which divides an incident ray into two rays.

[0036] In the following explanation, a separation amount is used to represent a distance by which a divided ray is away from an incident ray. Further, the separation direction is negative when a direction in which a divided ray is directed (see arrows designated by symbols  $\delta 1$ ,  $\delta 2$  and  $\delta 3$ ) is rotated clockwise with respect to the horizontal direction, and the separation direction is positive when the direction in which the divided ray is directed is rotated counterclockwise with respect to the horizontal direction.

[0037] As shown in Fig. 1, the first birefringence plate 1 has the separation direction of  $\theta 1$  and a separation amount of  $\delta 1$ . The second birefringence plate 2 has the separation direction of  $\theta 2$  and the separation amount of  $\delta 2$ . The third birefringence plate 3 has the separation direction of  $\theta 3$  and the separation amount of  $\delta 3$ .

[0038] In Fig. 1, a configuration, in which the separation direction  $\theta 1$  is negative, the separation direction  $\theta 2$  is  $0^\circ$  and the separation direction  $\theta 3$  is positive, is shown by way of example. In Fig. 1, the three birefringence plates 1-3 are separated for convenience of explanation. However, in actuality, the three birefringence plates 1-3 are cemented to each other.

[0039] In general, the cut-off function and the cut-off directionality of the OLPF is determined by an angle formed between separation directions of adjacent birefringence plates (hereafter, referred to as a separation angle) and the separation amount of each birefringence plate. When the separation angle is represented by a symbol  $\theta_s$ , the angle  $\theta_s$  is determined according to a following equation (1).

$$\theta_s = |\theta_1 - \theta_2| = |\theta_2 - \theta_3| \quad \cdots \cdots (1)$$

The angle  $\theta_s$  is regarded as an angle having a range of  $0^\circ$  through  $90^\circ$ .

[0040] As described below, the OLPF 10 according to the embodiment of the invention is configured to have both an excellent cut-off function and an excellent directionality. Hereafter, a detailed explanation to attain such optical performance will be made with reference to the drawings.

[0041] The separation angle  $\theta_s$  of the OLPF 10 satisfies a condition (2).

$$46^\circ \leq \theta_s \leq 60^\circ \quad \cdots \cdots (2)$$

[0042] Fig. 2 shows a MTF map when the separation angle  $\theta_s$  of the OLPF 10 is set to be  $46^\circ$ , i.e., when the separation directions of  $\theta_1$ ,  $\theta_2$  and  $\theta_3$  of the OLPF 10 are set to be  $0^\circ$ ,  $46^\circ$  and  $92^\circ$ , respectively. By making a comparison between Fig. 2 and Fig. 9, it is understood that the region E of the OLPF 10 according to the embodiment is larger than that of the conventional OLPF shown in Fig. 9. Further, as shown in the MTF

map of Fig. 2, the regions D scattering over the region E in the MTF map of the conventional OLPF shown in Fig. 10 are eliminated.

[0043] By satisfying the condition (2), the OLPF 10 according to the embodiment can attain not only the enhanced cut-off directionality but also the cut-off function better than that of the conventional OLPF.

[0044] Fig. 3 shows a MTF map when the separation angle  $\theta_s$  of the OLPF 10 is set to be  $48^\circ$ , i.e., when the separation directions of  $\theta_1$ ,  $\theta_2$  and  $\theta_3$  of the OLPF 10 are set to be  $0^\circ$ ,  $48^\circ$  and  $96^\circ$ , respectively. Fig. 4 shows a MTF map when the separation angle  $\theta_s$  of the OLPF 10 is set to be  $52^\circ$ , i.e., when the separation directions of  $\theta_1$ ,  $\theta_2$  and  $\theta_3$  of the OLPF 10 are set to be  $0^\circ$ ,  $52^\circ$  and  $104^\circ$ , respectively. Fig. 5 shows a MTF map when the separation angle  $\theta_s$  of the OLPF 10 is set to be  $55^\circ$ , i.e., when the separation directions of  $\theta_1$ ,  $\theta_2$  and  $\theta_3$  of the OLPF 10 are set to be  $0^\circ$ ,  $55^\circ$  and  $110^\circ$ , respectively.

[0045] As can be seen from Figs. 2-5, the difference between the size in the PL direction and the size in the PS direction of each of the regions A-D decreases, as the separation angle  $\theta_s$  increases from  $46^\circ$ . That is, by gradually increasing the separation angle  $\theta_s$  from  $46^\circ$ , the cut-off directionality can be further enhanced. With regard to cut-off directionality, the OLPF 10 inhibits the optimal symmetric property in each region when the separation angle  $\theta_s$  is set to be  $60^\circ$ .

[0046] However, as shown in Figs. 4 and 5, when the separation angle is set to be  $52^\circ$  or more, the region D becomes larger than the region E in each MTF map. This tendency becomes clearer when the separation angle  $\theta_s$  is set to an angle more than  $60^\circ$ . For this reason, the upper limit of the condition (2) is set to be  $60^\circ$ .

[0047] To further enhance the cut-off function and the cut-off directionality, the OLPF 10 may be configured to satisfy a condition (3).

$$46^\circ \leq \theta_s \leq 52^\circ \quad \cdots \cdots (3)$$

[0048] For example, the OLPF 10 having the separation angle of  $48^\circ$  has larger region E than the OLPF 10 having the separation angle of  $45^\circ$ . Further, the difference between the size in the PL direction and the size in the PS direction of each of the regions A-D of the OLPF 10 having the separation angle of  $48^\circ$  is sufficiently small and is substantially the same as that of the OLPF having the separation angle of  $90^\circ$ . Thus, the OLPF 10 having the separation angle of  $48^\circ$  exhibits further enhanced performance in which a balance between the cut-off function and the cut-off directionality is achieved.

[0049] It is also possible to adjust the cut-off directionality and the cut-off function by changing each of the separation amounts of the birefringence plates 1-3. More specifically, by making the separation amount  $\delta_1$  of the first birefringence plate 1 and the separation amount  $\delta_3$  of the third

birefringence plate 3 equal to each other, distortions of the shapes of the regions A-D in the MTF map can be sufficiently suppressed, and therefore the excellent cut-off directionality can be kept.

[0050] Further, as described in detail below, by changing the separation amount  $\delta 2$  of the second birefringence plate 2 relative to the other separation amounts  $\delta 1$  and  $\delta 3$  (which have been set equal to each other), the cut-off function and the cut-off directionality can be adjusted. That is, the OLPF 10 according to the embodiment may be configured to satisfy a condition (4).

$$\delta 1 = \delta 3 \neq \delta 2 \quad \cdots \cdots (4)$$

[0051] The change of the cut-off function and the cut-off directionality with respect to the change of the separation amount  $\delta 2$  will be explained. Figs. 6-8 represent MTF maps of the OLPF 10 having the same separation angle of  $48^\circ$  and having the separation amounts  $\delta 2$  of 1.0, 0.8 and 0.6, respectively. Further, in each of examples shown in Figs. 6-8, both of the separation amounts  $\delta 1$  and  $\delta 3$  are set to be 1.0.

[0052] By making a comparison between Fig. 6 and Fig. 7, it is understood that the difference between the size in the PL direction and the size in the PS direction of each of the regions A-D decreases, as the separation amount  $\delta 2$  decreases. Also, it is understood that a total size of the region A-D within a peripheral portion of the MTF map decreases as the separation

amount  $\delta 2$  decreases.

[0053] That is, by decreasing the separation amount  $\delta 2$ , both of the cut-off directionality and the cut-off functions are enhanced.

[0054] However, as can be seen from Fig. 8, the difference between the size in the PL direction and the size in the PS direction of each of the regions A-D becomes larger again as the separation amount  $\delta 2$  is further decreased from the situation shown in Fig. 7 (i.e.,  $\delta 2=0.8$ ). Further, in the case of Fig. 8, island shaped regions D clearly appear in an area neighboring to the regions A-D positioned at a central portion of the MTF map, by which the function of eliminating the high special frequency components of the OLPF 10 is deteriorated.

[0055] It is also understood from Fig. 6 that when the separation amount  $\delta 2$  is equal to the separation amount  $\delta 1$  ( $\delta 3$ ), the direction of PL coincides with the direction of the vertical direction. That is, the difference between the size in the PL direction and the size in the PS direction of each of the regions A-D starts to increase as the separation amount  $\delta 2$  increases from a certain value smaller than 1.0. When the separation amount  $\delta 2$  further increases from the situation shown in Fig. 6 (i.e.,  $\delta 2=1.0$ ), the cut-off directionality further deteriorates. Therefore, the separation amount  $\delta 2$  is required to be smaller than the separation amount  $\delta 1$  ( $\delta 3$ ).

[0056] For this reason, in order to further enhance the

performance, the OLPF 10 according to the embodiment may be configured to satisfy a condition (5).

$$0.5 \cdot \delta 1 \leq \delta 2 < 1.0 \cdot \delta 1 \quad \cdots \cdots (5)$$

It should be noted that  $\delta 1$  in the condition (5) can be replaced with  $\delta 3$ , since  $\delta 1$  and  $\delta 3$  are the same.

[0057] Although the present invention has been described in considerable detail with reference to certain preferred embodiments thereof, other embodiments are possible.

[0058] For example, the separation angle  $\theta_s$  may be changed within the range of the condition (2) or the condition (3) in accordance with a characteristic of light being incident on an imaging optical system which is provided together with the OLPF in an imaging apparatus (e.g., a digital camera), and/or performance of other optical components provided in the imaging apparatus, although in the above mentioned embodiment it is explained that the optimal separation angle  $\theta_s$  is  $48^\circ$ .

[0059] That is, an optimal separation angle may be determined by conducting sensory testing on images captured by the imaging apparatus.

[0060] The present disclosure relates to the subject matter contained in Japanese Patent Application No. P2003-074983, filed on March 19, 2003, which is expressly incorporated herein by reference in its entirety.